

Pulsar Astrometry with the VLBA

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Abstract. Many features of the Very Long Baseline Array (VLBA) contribute to make it the best telescope for pulsar astrometry. The measured proper motions and parallaxes allow distances and transverse velocities to be determined. These in turn provide clues to questions spanning nuclear astrophysics on scales of 10^{-23} m to the distribution of gas in the Galaxy on scales of 10^{20} m. Three pulsars are discussed in this paper. Among pulsars, B0950+08 has the most accurate VLBI-determined parallax. B1133+16 has a very high transverse velocity; its radial velocity is discussed. B0656+14 is a thermally detected neutron star. Determination of its distance has allowed its radius to be measured and its association with the Monogem ring supernova remnant (SNR) to be established, allowing a long-standing question in cosmic ray astrophysics to be addressed.

1. Introduction

Pulsars typically have velocities in the 100 to 1000 km s^{-1} range and preferentially populate the galactic plane. Thus sub-milliarcsecond astrometry is appropriate to determine distances and velocities of nearby ($\lesssim 3 \text{ kpc}$) pulsars. Most pulsar observations are forced to low radio frequencies ($< 2 \text{ GHz}$) in order to take advantage of their steeply inverted spectra ($S \propto \nu^\alpha$ with α typically in the range -2.5 to -1.5).

The VLBA is uniquely suited for astrometric pulsar observations. Parallax measurements require observations roughly every six months (but preferably every three months), making a full-time dedicated array such as the VLBA preferable. The wide field of view of the identical 25 m antennas allows one to find and make use of in-beam calibrators with a success rate of about 70% at $\lambda = 20 \text{ cm}$. These nearby calibrators make high-precision astrometry much simpler. The VLBA correlator has a pulsar gate allowing the signal-to-noise of pulsar observations to be increased by a factor of between about three and five, depending on the narrowness of the pulsar's pulse profile, by disabling correlation during the off-pulse portion of the pulsar's period.

2. VLBI astrometry

Astrometry is the science of precise localization of astronomical objects. Several measurements of an object over the span of a year or more can yield the proper

motion and annual parallax of the object. VLBI is well suited for precision position measurements because of the high resolution attainable with content-sized baselines. The phases, ϕ , of the measured visibilities are directly related to the location of the object:

$$\phi(\nu) = \frac{\nu}{c}(u l + v m) + \epsilon(l, m, t, \nu). \quad (1)$$

Here c is the speed of light, ν is the observing frequency, (u, v) is the projected baseline vector, and (l, m) is the location of the object being observed relative to the correlator model phase center. Added to the phase is an error term, ϵ , that varies with direction, time (t), and frequency. Phase-referencing is almost always used in VLBI astrometry. This form of relative astrometry observes a calibrator source with an accurately known position in a *nodding* cycle with the target (pulsar). At 20 cm with the VLBA, this cycle typically consists of about 90 s on the calibrator followed by about 120 s on the target. This cycle is repeated dozens of times per observation. Since the position of the calibrator source is well known and placed at the phase center during correlation, its visibility phases can be used to estimate the phase error:

$$l_{\text{cal}} = m_{\text{cal}} = 0 \longrightarrow \epsilon_{\text{cal}} = \phi_{\text{cal}}. \quad (2)$$

Since the calibrator was chosen to be nearby the target, and the observations of the target and calibrator are interleaved on a timescale short compared to that of the evolution of ϵ , the remaining phase error that remains after removing the interpolated calibrator phase from the target phase is much reduced:

$$\Delta\epsilon = \epsilon - \epsilon_{\text{cal}} \ll \epsilon. \quad (3)$$

While much reduced from the initial phase error, $\Delta\epsilon$ can remain substantial. This remaining error term is usually dominated by tropospheric and ionospheric gradients. The troposphere introduces a frequency independent delay, which corresponds to a phase error that is proportional to frequency. The ionosphere has a dispersive delay with a phase inversely proportional to frequency. Thus to first order,

$$\Delta\epsilon = \underbrace{A(l, m, t)}_{\text{Troposphere}} \nu + \underbrace{B(l, m, t)}_{\text{Ionosphere}} \nu^{-1}. \quad (4)$$

Two methods have been used in pulsar astrometry to improve phase-referenced astrometry. The first aims at minimizing the uncalibratable errors and the second aims at modeling and removing dominant errors.

2.1. In-beam calibration (Chatterjee et al., 2001)

Since both A and B increase with increased target-calibrator separation, it is advantageous to find a calibrator as near the target as possible. If the target and calibrator can both be placed within the primary beam of all of the antennas in the array ($\sim 25'$ at 20 cm for the VLBA), then both sources may be simultaneously imaged. The simultaneity also improves the phase-referencing. Two correlator passes are needed in almost all cases.

2.2. Ionosphere removal (Briskin et al., 2000)

For $\lambda \gtrsim 6$ cm the ionosphere dominates the phase error. At $\lambda \sim 20$ cm, the ionosphere is responsible for about 90% of the phase error. Because the ionospheric phase errors have a different frequency dependence than the tropospheric phase errors and the geometry (i.e., the pulsar's location), observations made over a substantial fractional bandwidth allow the ionosphere strength above each antenna, B , to be deduced. The frequency agility of the VLBA allows 8 independently tunable spectral windows to be placed within a 500 MHz portion of a band, providing enough leverage to measure and remove the ionospheric component of phase error. This method works well for target-calibrator separations up to about 3.5° , as long as both sources are strong enough and do not exhibit structure that changes significantly across the observed band.

3. Astrometry of PSR B0950+08 (Briskin et al., 2002)

In 1998 and 1999, VLBA observations of PSR B0950+08 were used to develop the ionospheric removal technique. A demonstration of the importance of improving phase-referencing is shown in Figure 1. After three successful epochs of observation, a parallax for B0950+08 was determined and a project to measure parallaxes of ten pulsars began. The proper motion and parallax measurements of B0950+08 improved considerably with the addition of four more epochs. Eight of the other pulsars each had four or five observations over the course of one year, resulting in parallaxes and proper motions. The tenth pulsar was never detected.

An eighth observation of B0950+08 occurred in October 2002 as part of NRAO's Mark 5 development. The Mark 5 disc-based VLBI recording system is being developed by Haystack Observatory as a replacement for the aging and bandwidth-limiting tape recorder systems currently deployed at almost all VLBI antennas. Mark 5 promises increased recording bandwidth, higher reliability and less expensive media. Although this additional observation was made using only Pie Town, Hancock and St. Croix antennas and did not employ the pulsar gate, it did further constrain the proper motion of B0950+08. A final fit to all eight epochs yielded a (J2000) proper motion of $\mu_\alpha \cos \delta = -2.06 \pm 0.07 \text{ mas yr}^{-1}$, $\mu_\delta = 29.37 \pm 0.05 \text{ mas yr}^{-1}$, and a parallax of $\pi = 3.81 \pm 0.07 \text{ mas}$ (all quoted uncertainties in this paper are 68% confidence intervals). A plot of the motion of B0950+08 and its proper motion and parallax fit is shown in Figure 1.

4. The radial velocity of B1133+16

B1133+16 is a bright, fast moving pulsar with characteristic age $\tau_{\text{char}} = 5 \text{ Myr}$. Its distance, $D = 357_{-19}^{+22} \text{ pc}$, and transverse velocity, $v_\perp = 636 \pm 40 \text{ km s}^{-1}$ were measured with the VLBA using the ionosphere removal technique (Briskin et al., 2002).

The radial velocities of pulsars are unmeasurable, although in a few cases they can be inferred. B1133+16 has a high galactic latitude, $b = 69.2^\circ$. If the true age τ and the birth height z_0 are known, then the radial velocity v_r can be

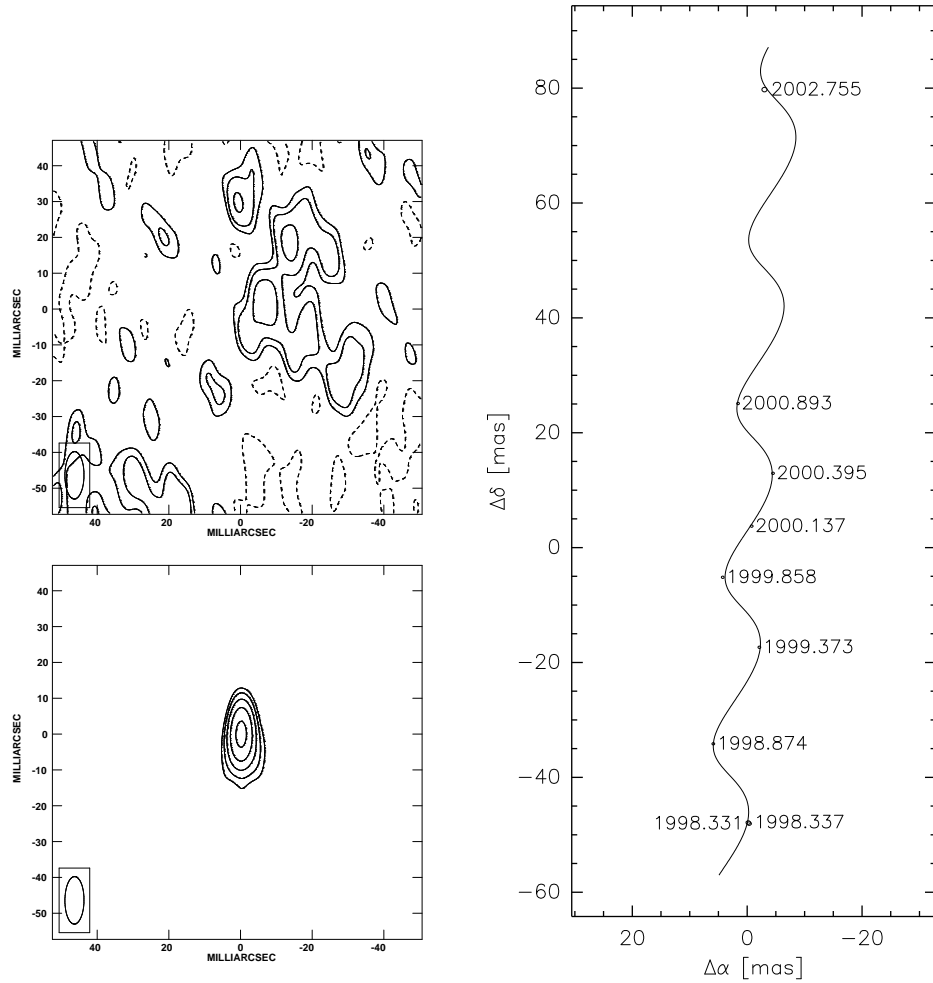


Figure 1. Ionospheric removal applied to B0950+08. On the left is an example of an image of B0950+08 before (above) and after (below) removal of the ionospheric phase errors. The contours are the same in each figure, increasing by factors of 2 from the lowest contour at 5 mJy beam^{-1} . On the right are the measured positions of B0950+08 at 8 different epochs. The best fit parallax and proper motion model is shown as the solid line. Note that the sizes of the ellipses are representative of the measurement uncertainties.

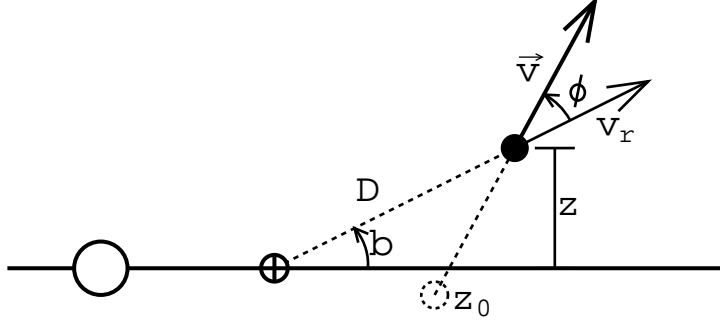


Figure 2. The geometry used to calculate radial velocities. The horizontal line represents the plane of the galaxy; the large circle is the Galactic center. Earth is the circle with the ‘+’ in the middle. The pulsar is born at the location of the dashed circle and is currently at the filled circle.

inferred from its current height above the galactic plane, $z = D \sin b$:

$$v_r = \frac{D \sin b - D \mu_b \tau \cos b - z_0}{\tau \sin b}. \quad (5)$$

See Figure 2 for a diagram of the geometry. The birth height is not known, so a sensible birth height distribution must be assumed. Here $P(z_0) \propto e^{-|z_0/a|}$ with scale height $a = 150$ pc is used. Likewise the true age is not known with certainty, so an age distribution based on the timing age is assumed as well. The probability distribution for v_r is then given by

$$P(v_r) = \int dz_0 \int dD \int d\tau \int d\mu_b \delta \left(v_r - \frac{D \sin b - D \mu_b \tau \cos b - z_0}{\tau \sin b} \right) \times P(z_0) P(D) P(\tau) P(\mu_b). \quad (6)$$

For many pulsars, this is quite non-constraining, but in the case of B1133+16, the result is significant. The inferred radial velocity is $v_r = -45_{-40}^{+60}$ km s⁻¹. That this is quite small compared to the transverse velocity means that this pulsar must be moving very nearly in the plane of the sky, $\phi = 99 \pm 9^\circ$.

5. PSR B0656+14

PSR B0656+14 is an adolescent pulsar with timing-derived age of 110 kyr. A five-epoch observing campaign was started with the goal of determining its distance to 10%. With a distance measurement, its thermal spectrum would reveal its radius.

5.1. Distance and Radius (Briskin et al., 2003)

Using a nearby bright in-beam calibrator, a (J2000) proper motion of $\mu_\alpha \cos \delta = 44.07 \pm 0.64$ mas yr⁻¹, $\mu_\delta = -2.40 \pm 0.29$ mas yr⁻¹, and a parallax of $\pi =$

3.47 ± 0.36 mas were fit to the five epochs of data. The distance derived from this measurement, 288^{+33}_{-27} pc, is less than half the distance estimated from its dispersion measure.

Several pulsars and radio-quiet neutron stars are known to emit blackbody radiation. A distance measurement combined with the spectral energy distribution can thus yield a blackbody radius. Observations in the optical, UV and x-ray are fit well by a three component model consisting of a soft blackbody representing the neutron star surface with a temperature of ~ 8.2 K ($8.4 \pm 0.3 \times 10^5$ K, Koptsevich et al., 2001; $8.0 \pm 0.3 \times 10^5$ K, Pavlov et al., 2002), a hard blackbody representing the polar cap regions with a temperature of $1.6 \pm 0.3 \times 10^6$ K (Pavlov et al., 2002), and a power law spectrum, presumably from the magnetosphere. If it is assumed that a pure blackbody accurately describes the emission from the surface of the neutron star, then the VLBA distance of 288 pc would imply an unrealistically small observable radius, $R_\infty \equiv R(1 - 2GM/Rc^2)$, of between 6.9 and 8.5 km.

A blackbody spectrum becomes distorted in the presence of an atmosphere. Several neutron star atmosphere models have been considered, but most of these produce radii that are either implausibly small or large. The most realistic radius results from application of a magnetic hydrogen atmosphere (e.g., Shibano et al., 1993). A range of radii are supported by the various magnetic hydrogen atmosphere models present in the literature, but all lie in the range ~ 13 to ~ 20 km. This range of radii does not usefully constrain the equation of state of matter at nuclear density, but additional phase-resolved optical observations and an improved distance through additional VLBA observations will likely shrink this range considerably.

5.2. Connection with the Monogem Ring (Thorsett et al., 2003)

The Monogem ring is a $\sim 25^\circ$ diameter soft x-ray shell. Although this source has been speculated to be a SNR, positive identification has been difficult as the source is not well seen in other wavebands, especially the radio. If this source is assumed to be a SNR, then modelling suggests a distance of about 300 pc and an age of about 86 kyr. Earlier attempts to associate B0656+14 with this SNR have been dismissed because of the pulsar's 760 pc dispersion measure distance. The VLBA distance measurement of B0656+14 agrees well with the SNR distance, and the ages are consistent with one another. Thus it is claimed that the same supernova event created the Monogem ring and B0656+14.

5.3. The cosmic ray spectrum ‘knee’ (Thorsett et al., 2003)

Above 10^{10} eV, the cosmic ray spectrum has only two distinct features: a *sharp* steepening at $\sim 3 \times 10^{15}$ eV called the ‘knee’, and a flattening around 3×10^{18} eV called the ‘ankle’ (see Wefel 2003 for a review). Although many possible explanations have been given, the sharpness of the knee has been difficult to explain. Erlykin & Wolfendale (1997) noted that a single dominant nearby source, rather than a superposition of many sources with varying properties or instrumental/propagation effects, would most easily explain the sharpness. They suggested that the knee could be a cosmic ray excess due to accelerated oxygen and iron nuclei from a 90 to 100 kyr old, 300 to 350 pc distant SNR. The Monogem

ring, now quite firmly established as a SNR of nearly the right age and distance, is proposed as the likely source.

6. Conclusion

Pulsar astrometry has made great advances with the VLBA. Eleven of the thirteen VLBI pulsar parallax measurements have occurred in the last 3 years using the VLBA. Techniques have been demonstrated on ordinary pulsars, such as B0950+08, pulsars with special interests have been targeted, such as B0656+14, and ongoing is a VLBA large project aiming to increase by a factor of two or three the sample of pulsars with parallax derived distances. Accurate distances and velocities of a sizable number of pulsars will allow the velocity distribution of pulsars to be probed with greater precision than currently possible and will improve Galactic electron density models, which will allow better estimates of distances to pulsars that do not have measured parallaxes. Accurate astrometry also promises to improve the statistics on spin-velocity alignment. Much increased bandwidth will likely be available within the next decade, bringing many more interesting pulsars within the sensitivity limits of the VLBA.

References

- Briskin, W. F., Benson, J. M., Beasley, A. J., Fomalont, E. B., Goss, W. M., & Thorsett, S. E. 2000, *ApJ*, 541, 959
- Briskin, W. F., Benson, J. M., Goss, W. M., & Thorsett, S. E. 2002, *ApJ*, 571, 906
- Briskin, W. F., Thorsett, S. E., Golden, A., & Goss, W. M. 2003, *ApJ*, 593L, 89
- Chatterjee, S., Cordes, J. M., Lazio, T. J. W., Goss, W. M., Fomalont, E. B., & Benson, J. M. 2001, *ApJ*, 550, 287
- Erlykin, A. D. & Wolfendale, A. W. 1997, *J. Phys. G: Nucl. Part. Phys.*, 23, 979
- Koptsevich, A. B., Pavlov, G. G., Zharikov, S. V., Sokolov, V. V., Shibanov, Yu. A., & Kurt, V. G. 2001, *A&A*, 370, 1004
- Pavlov, G. G., Zavlin, V. E., & Sanwal, D. 2002, in *Neutron Stars, Pulsars, and Supernova Remnants*, ed. W. Becker, H. Lesch, & J. Trümper (Garching bei München: Max-Planck-Institut für extraterrestrische Physik), 273
- Shibanov, Yu. A., Zavlin, V. E., Pavlov, G. G., Ventura, J., & Potehkin, A. Yu. 1993, in *Isolated Pulsars*, ed. K. A. Van Riper, R. I. Epstein, & C. Ho (Cambridge, UK: Cambridge Univ. Press), 174
- Thorsett, S. E., Benjamin, R. A., Briskin, W. F., Golden, A., & Goss, W. M. 2003, *ApJ*, 592L, 71
- Wefel, J. P. 2003, *J. Phys. G: Nucl. Part. Phys.*, 29, 821